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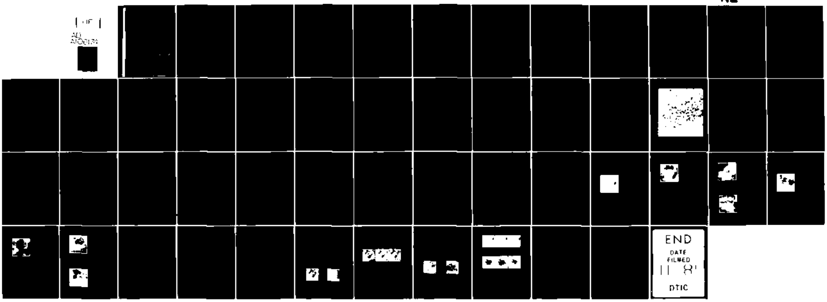

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Final Technical Report

by

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H. Kazmierczak, M. Stiles

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London England

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A procedure for the automatic extraction of roads from aerial images has been implemented on a DEC VAX 11/780 computer. The main parts of the procedure, i.e. the method for recognition of starting points on roads and two complementary methods for extraction of roads, are described. Modifications for extracting other line shaped objects, i.e. rivers and highways, are explained. A detailed documentation of the test results in different aerial images is presented. An assessment of the results as well as of the potentials and the limitations of the procedure conclude this report.

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Contents

Preface

The Research reported in this document has been made possible through the support and sponsorship of the U.S. Government through its European Research Office. This report is intended only for the internal management use of the Grantee and the U.S. Government.

The work was performed in the period of October 1979 to March 1981.

1. Statement of the problem

Methods for an interactive extraction of roads from aerial imagery have been developed and demonstrated successfully /1,2/. This report contains a description of three major goals for improvement and extension of those methods already existing:

- development of an automatic procedure to identify and locate starting points for the extraction methods
- development of several modifications to solve the problems of the extraction of line shaped objects other than roads
- test and evaluation of all methods in large area imagery

It was the aim of this research project to develop and demonstrate the automatic extraction of certain classes of line shaped objects from large area imagery (aerial images 9" by 9" at a scale of 1 : 74 000). More specifically, we addressed the problems of the extraction of roads, rivers, railroads and multilane highways, where the operator only has to input certain feature parameters describing the object class, the image scale, etc. and the extraction starts and proceeds autonomously.

The implementation of the different methods as a single computer program system, which runs on our computer VAX 11/780, is described in a seperate report /3/. In the following, a description of the methods will be presented and the results will be documented and discussed. A complete printout of the computer program is added as a separate document. A magnetic tape with all source files is available from USAETL.

2. Short description of two methods for the extraction of line shaped objects from aerial photographs

To solve different problems of the extraction of line shaped objects, two different methods have been developed which complement each other perfectly. The basic idea of the extraction

methods is the analysis of one or more locally limited gray level functions. As we do not process the whole image systematically to produce locally isolated line segments, but proceed on an object guided basis from already known line segments to look for a continuation of the line object, we can predict the most probable location, orientation and properties of possible neighbouring segments. Thus we even do not have to process 2D submatrices of pixels, but can confine the computations to the analysis of 1D gray level profiles, which are perpendicular to the predicted object orientation. More specifically, we are looking for the very next cross section or a limited sequence of successive cross sections of the object to be extracted.

In the following, a short description of the basic operator for gray level profile analysis and the two extraction methods is presented. For more details see /4,5,6,7/.

2.1 Profile analysis operator

The profile analysis operator (PAO) performs a special analysis of a 1D gray level function $g = f(x)$. It is the purpose of the PAO to produce for each point of the function a profile characteristic pc which consists of two profile element digits ped_1 and ped_2

$$pc = (ped_1, ped_2)$$

Let v and e be two variables which may be called gray level variance and range variance. The definition of the function to calculate pc is given indirectly through the two functions to calculate ped_1 and ped_2 :

$$
\mathrm{ped}_1(x) = \begin{cases}
1: & \text{i)} \quad g(r) \leq g(x) + v \qquad \forall r \in [x-e,\ x) \subset \mathbb{R} \\
 & \text{ii)} \quad \exists r_0 \in [x-e,\ x) \subset \mathbb{R}: \\
 & \qquad g(r) \leq g(x) - v \qquad \forall r \in [x-e,\ r_0] \subset \mathbb{R} \\
2: & \text{i)} \quad g(r) \geq g(x) - v \qquad \forall r \in [x-e,\ x) \subset \mathbb{R} \\
 & \text{ii)} \quad \exists r_0 \in [x-e,\ x) \subset \mathbb{R}: \\
 & \qquad g(r) \geq g(x) + v \qquad \forall r \in [x-e,\ r_0] \subset \mathbb{R} \\
3: & g(x)-v < g(r) < g(x)+v \qquad \forall r \in [x-e,\ x) \subset \mathbb{R} \\
0: & \text{else}
\end{cases}
$$

$$
\mathrm{ped}_2(x) = \begin{cases}
1: & \text{i)} \quad g(r) \leq g(x) + v \qquad \forall r \in (x,\ x+e] \subset \mathbb{R} \\
 & \text{ii)} \quad \exists r_0 \in (x,\ x+e] \subset \mathbb{R}: \\
 & \qquad g(r) \leq g(x) - v \qquad \forall r \in [r_0,\ x+e] \subset \mathbb{R} \\
2: & \text{i)} \quad g(r) \geq g(x) - v \qquad \forall r \in (x,\ x+e] \subset \mathbb{R} \\
 & \text{ii)} \quad \exists r_0 \in (x,\ x+e] \subset \mathbb{R}: \\
 & \qquad g(r) \geq g(x) + v \qquad \forall r \in [r_0,\ x+e] \subset \mathbb{R} \\
3: & g(x)-v < g(r) < g(x)+v \qquad \forall r \in (x,\ x+e] \subset \mathbb{R} \\
0: & \text{else}
\end{cases}
$$

For simplicity reasons, the pair of $ped_1(x)$ and $ped_2(x)$ values will be written as a number with two digits, which is then called profile characteristic pc of g at the location x. The set of possible pc values is

$$\{00, 01, 10, 11, 02, 20, 22, 03, 30, 33, 12, 21, 13, 31, 23, 32\}$$

Fig. 1 gives an example of the calculation of $pc(\hat{x})$:
A rectangle with a height of 2 * v and a length of 2 * e.

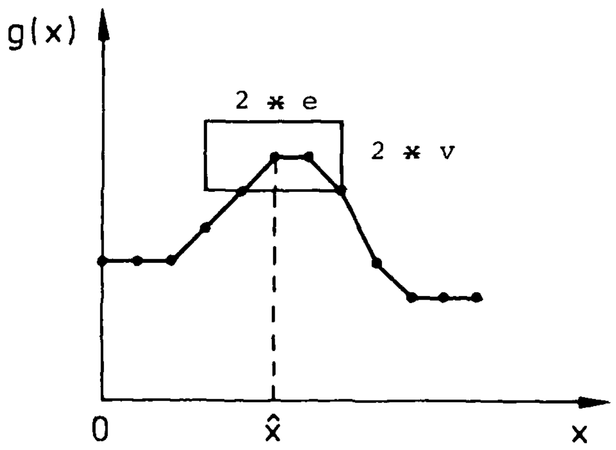


Fig. 1: Example of the calculation of $pc(\hat{x})$.

is centred on the location $(\hat{x}, g(\hat{x}))$. As the curve g(x) intersects only the bottom side of the rectangle, we get the value 1 for both $ped_1(\hat{x})$ and $ped_2(\hat{x})$ functions. Thus the profile characteristic at the location $\hat{x}$ results in

$$pc(\hat{x}) = 11$$

To explain the meaning of the different pc's, it can be stated, that pc(x) = 11 results from a local maximum of g at or near x and that pc(x) = 22 results from a local minimum of g at

or near x, etc. Note, that the pc values are computed by considering a smaller or larger neighbourhood of the respective location x, where this neighbourhood is defined by the variables v and e.

The second processing step of the PAO leads to a partitioning of the definition domain of g(x) into different intervals: all neighbouring locations x with identical pc constitute an interval. Each interval carries as an index the pc of the locations which it comprises. In general, the main property of the PAO is that it expands local features of single points such as "local maximum in x" to intervals of the definition domain which contain x Note, that different partitioning into intervals of a function g(x) will result of the application of the PAO with different values for the variables v and e. For some applications of the PAO to be explained in the following, only one predetermined set of values for the variables v and e is used. For other applications, several sets of values for v and e are used sequentially and the stability or instability of the resulting set of partitions is evaluated.

2.2 The local method for line extraction

The local method for extraction follows each line object on a step by step basis. The basic procedure is the following: Suppose that some parts of a line object have already been extracted. With the knowledge about these object parts,

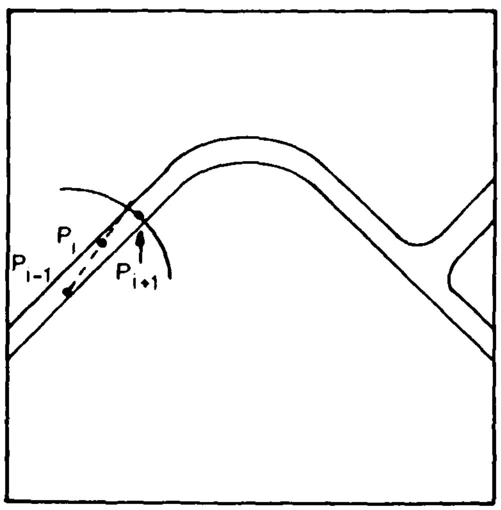
- the location
- the orientation
- the necessary object features such as contrast to the surrounding, width, pc of a cross section

of a possible continuation of the line object are predicted and tested via gray level diagram analysis. In the case of compliance

with the predicted features, this next increment of the line object is accepted. In the case of noncompliance, more sophisticated algorithms are applied to decide, whether the line object continues with changed feature values or ends at that point. The following main parts constitute the local method to be described in more details.

Definition of the next sample line for gray level diagram evaluation

Consider the case of an idealized example shown in fig. 2. The sample points P_{i-1} and P_i of the line object have already been extracted. The centre of the next sample line to detect the continuation of the object is predicted on a straight line extrapolation beyond P_i. The sample line is a part of a circle; it extends symmetrically on both sides of the centre. The distance between P_i and the centre is called step width s of the method, which normally has a default value of some pixels, depending on the scale of the image and the dimensions of the objects.



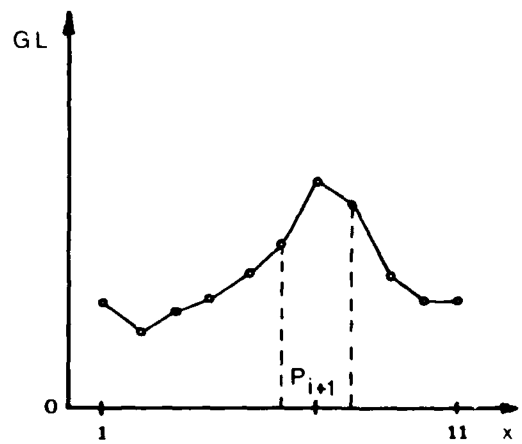


Fig. 2: Basic proceeding of the local method
a) prediction of point P_{i+1};
b) gray level diagram along the sample line.

The pixels of the sample line constitute a 1D gray level diagram (see fig. 2b), which is analysed by the PAO to verify a possible continuation of the object. During the extraction process, the normal step width s can be changed for several reasons:

- if the analysis of the respective gray level diagram is negative or ambiguous, the step width is decreased until a minimum value (usually 1 pixel) is reached. This decrease follows the idea, that the gray level diagram at a shorter distance from the current stand point can be interpreted more easily
- if the course of the object deviates from a straight line continuation or if some object features are changing, the step width is decreased for the following step
- if several extracted sample points of the objects form a straight line, the default step width is increased step after step up to a maximum value. This increase is justified by the fact that the straight line object continuation to be expected needs fewer sample points for the extraction.

Analysis of the sample line gray level diagram

The analysis of a new sample line gray level diagram is performed by the PAO using predicted values for v and e. Prediction is based on the v and e values of the last few successful analysis results of the PAO. All intervals of the partition of the gray level diagram are checked with respect to the following features, the values of which are predicted from the last few steps along the object:

- average gray level of the centre pixels of the interval
- width of the interval
- pc of the interval

In the case of compliance with the predicted values, the interval is accepted as the cross section of the object continuation. The centre point of the interval is added to the list of object points and is used as a basis for the search of the next increment of the object.

In the case that the features of more than one interval of a partition comply with the predicted values, object splitting, noise, or other unfavourable effects are suspected to be present at that location. As no straight forward decision for one of the candidates is possible, a new location for the object continuation is predicted at a shorter distance from the last object point and the gray level diagram analysis is repeated completely. In the case that no interval complies, a possible end of the object or a gap in the object is suspected at that location. The gray level analysis is repeated at a shorter step width.

Adaption of object features at each step

After the acceptance of a new object point, the next step is prepared by adapting the object features. The following parameters are adapted at each step:

- PAO parameters v and e
- object features: average gray level
  width of the object
  pc of the object
- step width

PAO parameters and object features are updated by averaging the respective values of the last few steps. The step width depends on the straightness of the last few increments of the object and the degree of compliance of their features.

Extrapolation steps to bridge small gaps of the object

An extrapolation step has a bigger step width than the maximum step width under normal conditions. The extrapolation step is applied if, at the current location, no normal continuation of the object was detected for several gray level diagram analyses with decreasing step width including the minimum step width.

As the reliability of detected object continuations decreases with increasing step width, the requirements for compliance of the object feature values with the predicted values are higher than in the normal case. For large extrapolation steps (15 to 20 pixels), the emphasis is placed on the analysis of the diagrams of two concentric, semicircular sample lines where a possible object continuation must be detected on both sample lines.

Thus it is possible to bridge smaller gaps of the object, provided that the object continuation can be detected unambiguously beyond the gap. Larger gaps or a series of several small gaps cannot and should not be bridged by this extraction method as there is too little evidence for accepting those results as reliable data on the basis of this procedure. The regional method to be described in the next section is applied in these cases.

Analysis of object intersections

An intersection of line objects may be present at a location, where the following conditions are true:

- the results of a series of analyses of gray level diagrams with decreasing step width contain two or more than two acceptable candidates for possible object continuations
- the width of a detected candidate is much larger than the expected value.

In these cases, the gray levels of a full circle sample line around the suspect location are presented to the PAO. The result of this analysis is used to confirm the intersection or discard it: if only two acceptable candidates are detected, where one of both is located on the object already extracted, the cue for intersection is deleted. If more than two acceptable candidates are detected with more than one pointing in new directions which were not yet covered, an intersection is defined at that location. All these candidates are taken for possible object continuations and are processed sequentially.

2.3 The regional method for line extraction

A detailed description of this method has already been produced for ERO /1/. For the completeness of this report, a summary of the basic ideas is presented here.

The regional method works in a predetermined limited part of the image (prediction of the area to be processed). This area called "area of interest" usually has a rectangular shape. The area of interest is expected to contain completely an interesting part of the line object to be extracted (see fig. 3 a).

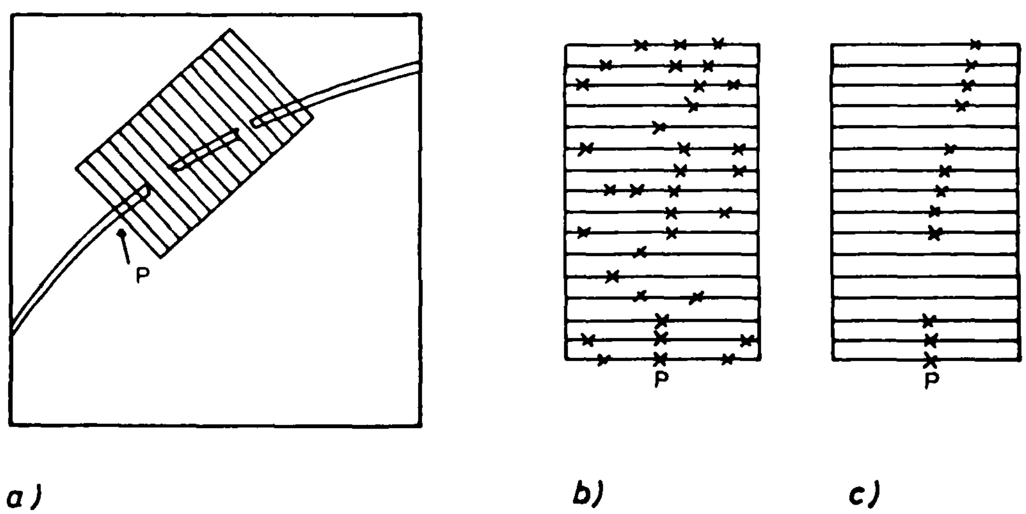


Fig. 3: Characteristics of the regional method.

In addition the orientation of the rectangle is supposed to comply with the predominant orientation of the object. It has been shown that a complete analysis of the 2D gray level matrix of the area of interest is not necessary to detect the continuation of a line object. The analyses of several 1D sample lines which possibly contain cross sections of the object, has proven to be sufficient.

The sample lines are perpendicular to the main axis of the rectangle. The first part of the line detection algorithm consists of a gray level analysis of the sample lines to discover candidates for object points. A confidence value is computed for each point of each sample line to indicate its probability of belonging to a line object. A semi threshold operation is applied to this matrix of confidence values to retain only a few points with the highest values of each sample line (see fig. 3 b).

The second part of the algorithm works on this set of candidates to detect subsets, the points of which are in a collinear position. This computation is done iteratively to increase the confidence value of a point, if collinear continuation points exist, or to decrease its confidence value otherwise. Thus it is possible to confirm all candidates, which contribute to form a line, while the more or less isolated candidates can be discarded. At the same time, two vectors have been computed for each confirmed candidate, which point to both neighbouring candidates in a line above and below. On the basis of this direction information and the last known object point P, the line following task is accomplished as the last part of this algorithm (see fig. 3 c).

Attention should be given to the fact, that the local and the regional method for line object extraction complement each other very well: While the first method is able to follow any curvature of the line object, to adapt changing features, to accommodate the necessary amount of computation and to detect line intersections, the second method is able to process noisy image data, to bridge gaps and to cope with badly visible objects. Thus the

cooperation between both methods in combination with a method for the automatic definition of starting points on the line objects provides a maximum of correctness and reliability of object extraction results with a minimum of computation.

3. Description of a method for the recognition of starting points for the automatic extraction of roads

The extraction methods work on an object guided basis, i.e. from the position of the lastly detected object segment, the position of a continuing object segment is predicted and the computations concentrate on that predicted position to verify or reject a new object segment. This basic procedure requires, that at least one initial starting position for each seperate object is given. As a first and most obvious method to define these starting points, an interactive procedure has been implemented, where the human interpreter detects a suitable starting point visually and inputs the coordinates manually. An automatic method for this task has also been developed and implemented, which works as follows: Several lines and columns of the image matrix are selected as sample lines to be analysed by the PAO. The values of the variables v and e are derived from the type of the object and the resolution of the image. All sample lines are partitioned into intervals as described in section 2.1. Only those intervals are accepted as candidates for starting points, the features of which comply with the predetermined object features, e.g. if we are interested in extracting roads of a certain width w and a positive contrast with the surroundings, only the intervals with pc = 11 and width w are accepted as candidates.

For verification, each candidate is analysed more closely by the following procedure (see fig. 4).

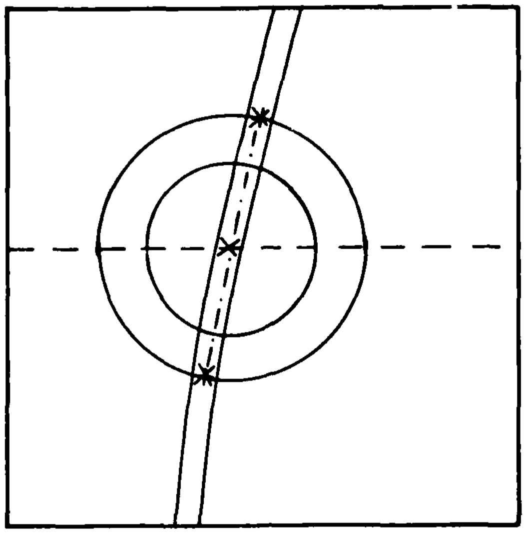


Fig. 4: To explain the verification of a starting point.

Two concentric circular sample lines around the candidate location are submitted to the PAO for gray level analysis. The interpretation of the partitioning of the sample lines has to comply with several requirements. A candidate is discarded as soon as the first noncompliance occurs:

- there must be at least two intervals on the smaller circle, which are located diametrically and the features of which (average gray level, width, pc value) comply with the respective features of the candidate

- there must be exactly two intervals on the bigger circle such that they are collinear with a pair of diametrical intervals of the smaller circle and that the features again comply with the respective features of the candidate

- the gray level variance along a sample line, which fits through the centres of all selected intervals (i.e. this sample line coincides with the suspected line object at that region, see fig. 4) is lower than a certain threshold value, the amount of which is set as a default value or can be chosen interactively.

If these requirements are fulfilled, we accept the candidate as a true starting point for an extraction attempt and - as the requirements are quite stringent - we are certain that it is a reliable starting point in most cases. Test results of this method are shown in section 5.

4. Modifications for the extraction of rivers and highways

4.1 Modifications for rivers

It has been found that no major modifications of the methods were necessary to handle the problems arising with the extraction of rivers from images, as long as they comply with the requirement of a line object: extreme length/width relation; width not bigger than approx. 10 pixels in an image matrix (the latter requirement can be satisfied for a wide range of applications by variation of image scale and digitization resolution).

The necessary modifications refer to some feature values only. In normal aerial images, rivers appear with negativ contrast to the surroundings, which is taken into account by defining pc = 22 for all methods. At the same time, the width of rivers usually varies to a higher extend than the width of roads, which can be accommodated by a higher threshold for the width variation tolerance in all methods. Low contrast with the surroundings or high curvature require the frequent change between both extraction methods while operating in a cooperative mode. Results are shown in section 5.

4.2 Modifications for the recognition of starting points on highways

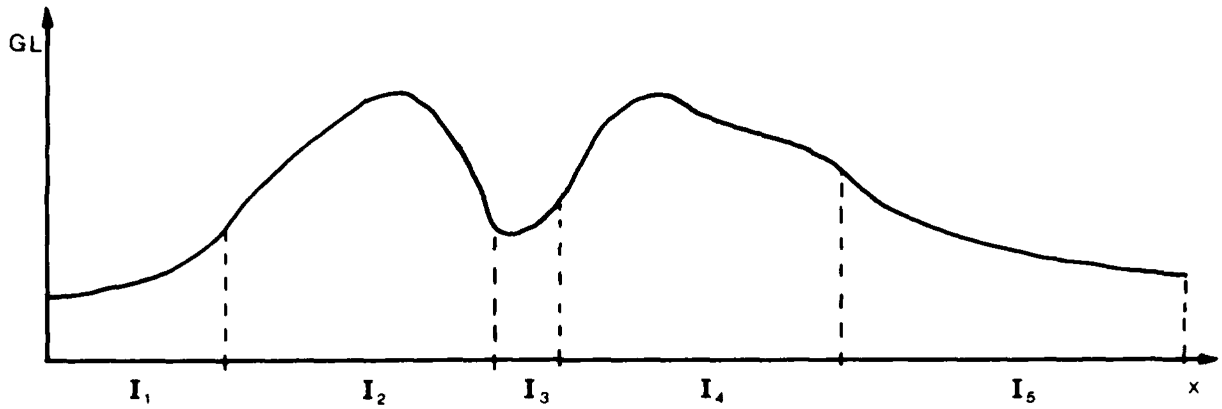
The application of the method for recognition of starting points (see section 3) to the problem of multi-line objects revealed two substantial constraints:

- the larger width of these objects could not be handled adequately
- The compound profile of such an object could not be handled adequately while analysing the gray level diagram of cross section sample lines.

To solve these problems, the method for recognition of starting points has been modified to process the image data at a reduced resolution and completed by a special verification part. The basic procedure now follows these ideas:

In comparison with the processing of normal single line objects, we reduce the resolution of the image by a factor of 3 to 5. After this operation, the separate lines of most multi-line objects merge into a single line, which - as the first part of the starting point recognition - allows the application of the original method with suitable parameter values. This reduction of resolution causes a substantial loss of object details which leads to a higher rate of misclassifications and false alarms, as a lot of objects resemble each other at that resolution (fields, yards, treeless areas in a forest, etc.). To compensate this deficiency, a verification has been added to decide, whether a preliminary starting point which has been accepted at the reduced resolution, can be accepted as a true starting point for a multi-line object. This verification algorithm works in the original, non-reduced image data resolution and essentially applies the same basic computations as described above. The preliminary starting point location is transformed from the reduced resolution

a)



b)

161	152	176	210	209	208	212	169	207	207	203	215	172	173	175	160	168
171	162	171	183	213	202	208	196	171	211	205	206	204	174	173	168	172
170	142	173	194	213	204	206	187	191	209	204	211	194	174	178	159	166
170	160	148	174	200	206	206	211	173	201	207	203	213	184	173	155	144
161	165	140	162	177	212	203	207	204	170	212	208	209	209	174	158	158
166	153	150	169	193	209	203	211	180	193	207	203	216	185	158	131	132
152	155	136	155	176	213	205	208	211	168	213	208	205	214	174	149	131
165	152	139	143	161	192	214	204	208	204	186	211	202	211	206	169	132
163	159	134	147	167	202	211	207	207	187	201	208	201	213	194	156	124
158	163	167	145	151	178	213	202	208	212	170	209	209	203	215	170	161

c)

2	2	12	11	11	11	11	22	11	11	11	11	20	20	20	20	20
2	2	2	12	11	11	11	12	22	11	11	11	11	20	20	20	20
2	22	2	11	11	11	11	22	22	11	11	11	11	20	21	20	20
2	2	22	12	11	11	11	11	22	11	11	11	11	21	21	21	20
2	2	22	2	12	11	11	11	11	22	11	11	11	11	21	20	20
1	22	22	12	11	11	11	11	22	21	11	11	11	21	21	20	20
2	2	22	2	12	11	11	11	11	22	11	11	11	11	21	21	20
1	22	22	22	12	12	11	11	11	11	22	11	11	11	11	21	20
1	1	22	22	12	11	11	11	11	22	11	11	11	11	21	21	20
2	1	1	22	22	12	11	11	11	11	22	11	11	11	11	20	20

<u>Fig. 5:</u> Details of the verification of a preliminary starting point for a highway
a) gray level profile; b) gray levels of the sample lines of an area of interest; c) the resulting pc values of the PAO.

image back into the non-reduced resolution image. An area of interest is placed at this location and several sample lines are submitted to the PAO for gray level analysis. It is the aim of this analysis of gray level diagrams perpendicular to the expected orientation of the object in the full resolution image to detect the individual parallel lines (e.g. the different lanes of a highway) for a comparison with the expected number, width and sequence (see fig. 5). An average width is computed for the intervals on all gray level diagrams which possibly represent the same line of the object. Explaining the example of fig. 5 further, we get a sequence of one bright, one dark, and one bright line with an average width of 4 pixels, 1 pixel, and 4 pixels respectively. If we searched for a starting point on a highway of this type and dimensions, we would finally accept this location as a true starting point and transfer the coordinates to the extraction method.

4.3 Modifications for the extraction of highways

Only the regional method has been modified appropriately to accommodate the problems of extraction of multi-lane highways. The modifications refer to a reduction of the image resolution for the normal extraction steps with the regional method and some verification tests which are performed in the original high resolution image to assure the reliability of the results and to exclude deviations of the extraction process.

Due to the processing of the reduced resolution image the extraction speed profits from a significant reduction of the amount of image data; on the other hand we need not worry about sharp bends which would complicate the extraction by the regional method: at a reduced resolution image the highways mostly follow a straight line and have only smooth curves.

After a predetermined number of extraction steps, the verification test as described in section 4.2 is performed to assure that the current multi-line object is still in the focus of the extraction process and no deviation to follow exits, neighbouring fields or tree lines has occurred. If the verification test reveals any doubt about the correctness of the extraction process (e.g. no compliance of the sequence of the different lines with the expected sequence), the verification is repeated immediately after the next extraction step. If the doubts persist, the extraction is stopped and reinitialized at the next starting point.

Thus we succeed again to produce reliable extraction results with a high degree of automation, taking into account the minor disadvantage that we sometimes miss a noisy or distorted part of the object. But the interactive completion of missing object parts is performed much more easily than the correction of false results.

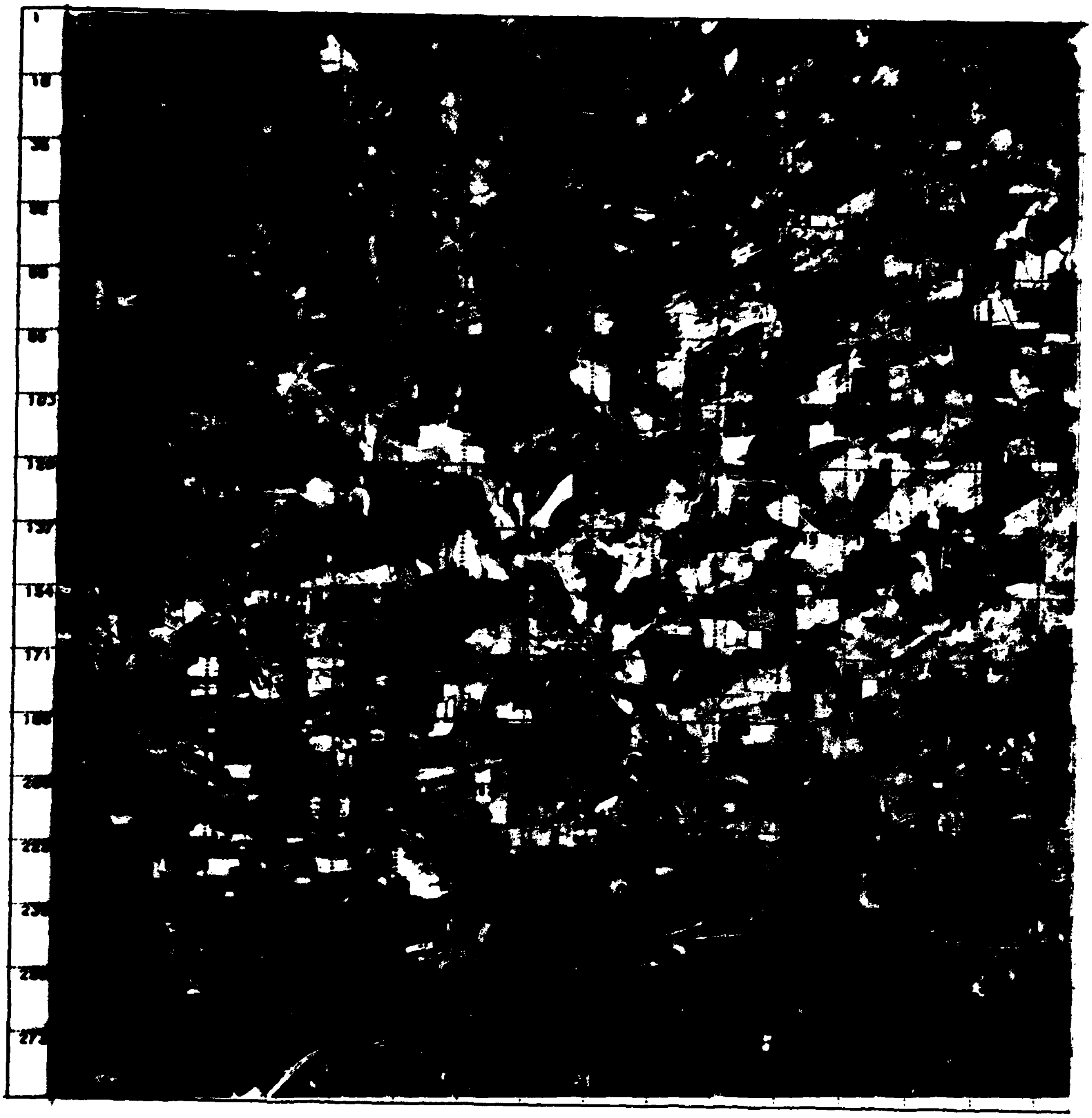
5. Results

5.1 Results of automatic extraction of roads from small scale, large area aerial photographs

The method for recognition of starting points and the two methods for extraction of roads - as described in sections 2 and 3 of this report - have been implemented and tested separately on our computer DEC PDP 11/70. After having achieved satisfactory results, all three methods were implemented for cooperative road extraction as a single computer software system on our DEC VAX 11/780. For details of the implementation refer to the supplementary report /3/.

Test results are shown and explained for an aerial photograph of 20 cm x 20 cm at a scale of 1 : 74 000 as supplied by USAETL. This image has been digitized on an OPTRONICS scanner to produce an image matrix of 8196 x 8196 pixels with 8 bit gray level resolution. The image matrix has been partitioned into a mosaic of 17 x 17 overlapping subimages of 512 x 512 pixels each. Each subimage corresponds to an area of approx. 1 km x 1 km and needs - as an average value - a computation time of approx. 1 min, input data transfer, processing and storing of the results included. Fig. 6 shows the test image with an overlay to indicate the location of each of the 289 subimages.

A short analysis of the image contents revealed that a great variety of roads is present in the imaged area. To get a complete overview of the methods´s performance, we processed this image several times with different values for the parameter "width". All other parameters were set to their default initial values and were adapted during the process as described in section 2. The results of the different runs are presented in the following figures.



<u>Fig. 6:</u> The complete test image with an overlay of the position of each subimage.

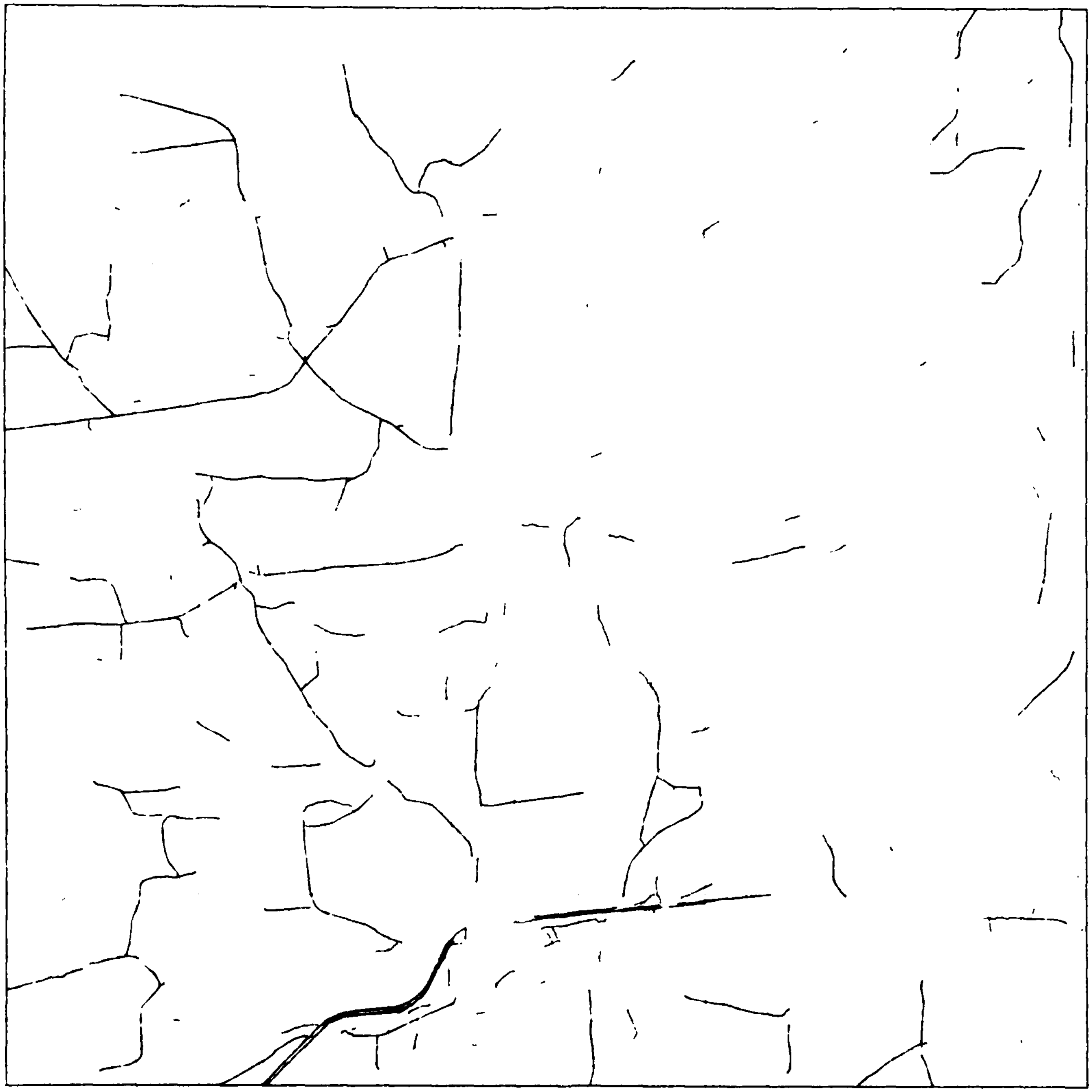


Fig. 7: Extraction results for small roads of 2 to 4 pixels.

The first run was started with an object width tolerance of 2 to 4 pixels. This means that we address the small roads or separate single lanes of highways selectively, because for our digitization, a pixel corresponds to a circular area of approx. 2 m diameter on the ground. Fig. 7 shows the result of this run, which needed 4 : 43 hours of processor time on the VAX 11/780 for the complete mosaic of 289 subimages, including data transfer to and from the disc storage.

It can be seen that a lot of connected roads has been extracted, especially in the left half of the image. Furthermore, there appear some short segments of roads isolated from each other (note, that at this scale, a line segment of 1 cm corresponds to a road length of approx. 700 m on the ground) and there remain some gaps between large connected parts of the network of roads.

A second run was initialized with an object width tolerance of 3 to 6 pixels (corresponding to approx. 6 m to 12 m on the ground to address the medium size roads. The result is shown in fig. 8.

The processing time for this run was 4 : 49 hours in total. With reference to fig. 6 and fig. 7, it can be seen that most of the small roads were also detected during this run that some gaps in the results of the first run could be bridged (see subimages No. 58, 59, 156, 193, 215, etc.) and that a considerable amount of extended parts of roads have been detected in addition to the results of the first run (especially in the right half of the image, see subimages No. 28, 44, 61, 78, 95, 112, 113, 233, 234, 218, 219, etc.).

Fig. 8: Extraction result for medium size roads of 3 to 6 pixels.

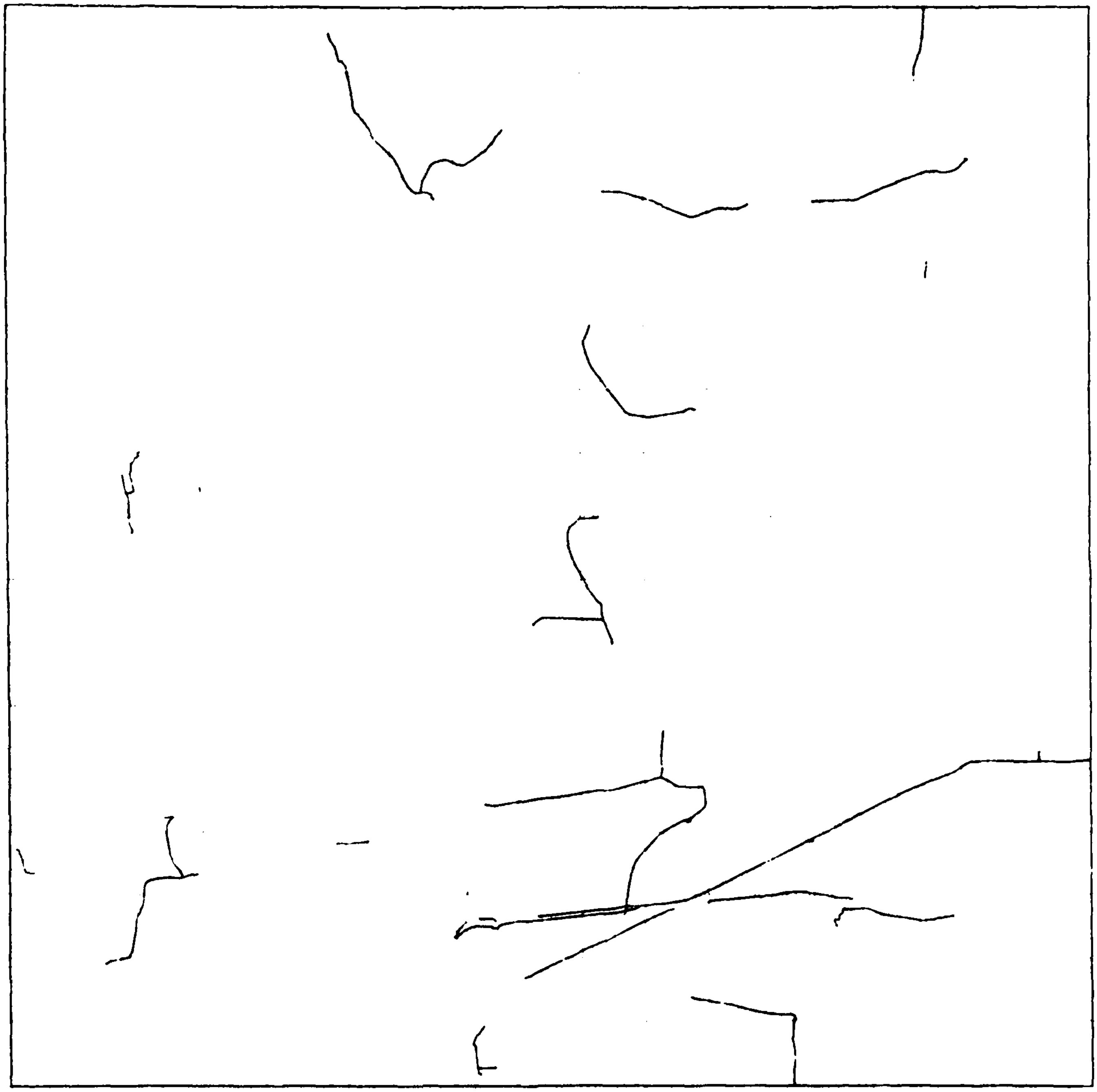


Fig. 9: Extraction results for broad roads of 5 to 8 pixels.

A third run was initialized to address the broad roads and highways. The width tolerance was set to 5 and 8 pixels. The results are shown in fig. 9.

The processing time of this run amounted to 3 : 24 hours. It can be seen from the results, that practically none of the smaller roads is detected in this run, but a few parts of the network of roads, especially in the lower right section of the image, have been found in addition to the previous results. The processing time is only by a factor of 1/3 shorter than for the first two runs; this is due to the fact, that all subimages have to be transferred to the working storage, which takes a considerable amount of the computing time, and the search for starting points is performed in all subimages, but was successful with this parameter setting only in a few subimages.

As an interesting experiment, we superposed the results of all three runs to one another (see fig. 10).

By comparison of this results with the aerial image (fig. 6) it can be stated that

- the bigger part of the network of roads (approx. 80 % to 90 %) has been extracted automatically with no interaction

- practically no errors occurred during the automatic extraction process. A very few amount of false results may be noticed (e.g. in subimages No. 121, 248 and 252)

- a considerable number of gaps between bigger parts of the network of roads still remain. A closer look at the image data reveals that at the position of most of these gaps the respective road cannot be detected locally. In most cases the road is hidden by trees or shows no contrast to the surrounding area. Some of these problems will be analysed in more detail in the following.

Fig. 10: Superposition of the results of all three runs.

- a few very short segments of line objects were detected with no continuation (see subimages No. 14, 30, 89, 100, 119, 197). In fact, most of these segments are located in forest areas, were starting points could be detected, but the extraction methods decided that no reliable continuation was possible (see subimages No. 14, 30, 89, 119, 197 in fig. 6). It would have been an easy task to erase these spurious results on the basis of a minimum length threshold. But we decided not to do the deletion at first hand, because some of these short segments are true parts of the roads and could be very useful to a later higher sophisticated automatic method for the completion of the extraction process (see subimages No. 33, 53, 133, 150, 175). These short segments also could support an interactive completion of the extraction results, after which an automatic postprocessing would erase the rest of the segments, which at that status of the processing would have been definitely identified as false results.

To investigate the properties of the methods further, we initiated another two runs with different parameter values. Fig. 11 shows the results of a run where the object width tolerance was set between 2 and 5 pixels.

It turns out that this run produced the most complete result of the roads, but needed the highest amount of computer time (5 : 10 hours for the whole set of 289 subimages). The comparison of this result with the results in fig. 7 and fig. 8 shows that a single run with optimized parameter values can produce approximately the same results as two runs with a selective parameter setting for specific object classes. This demonstrates very clearly both the flexibility and the sensitivity of the automatic extraction process, which can be adapted to a variety of extraction problems by specific parameter values.

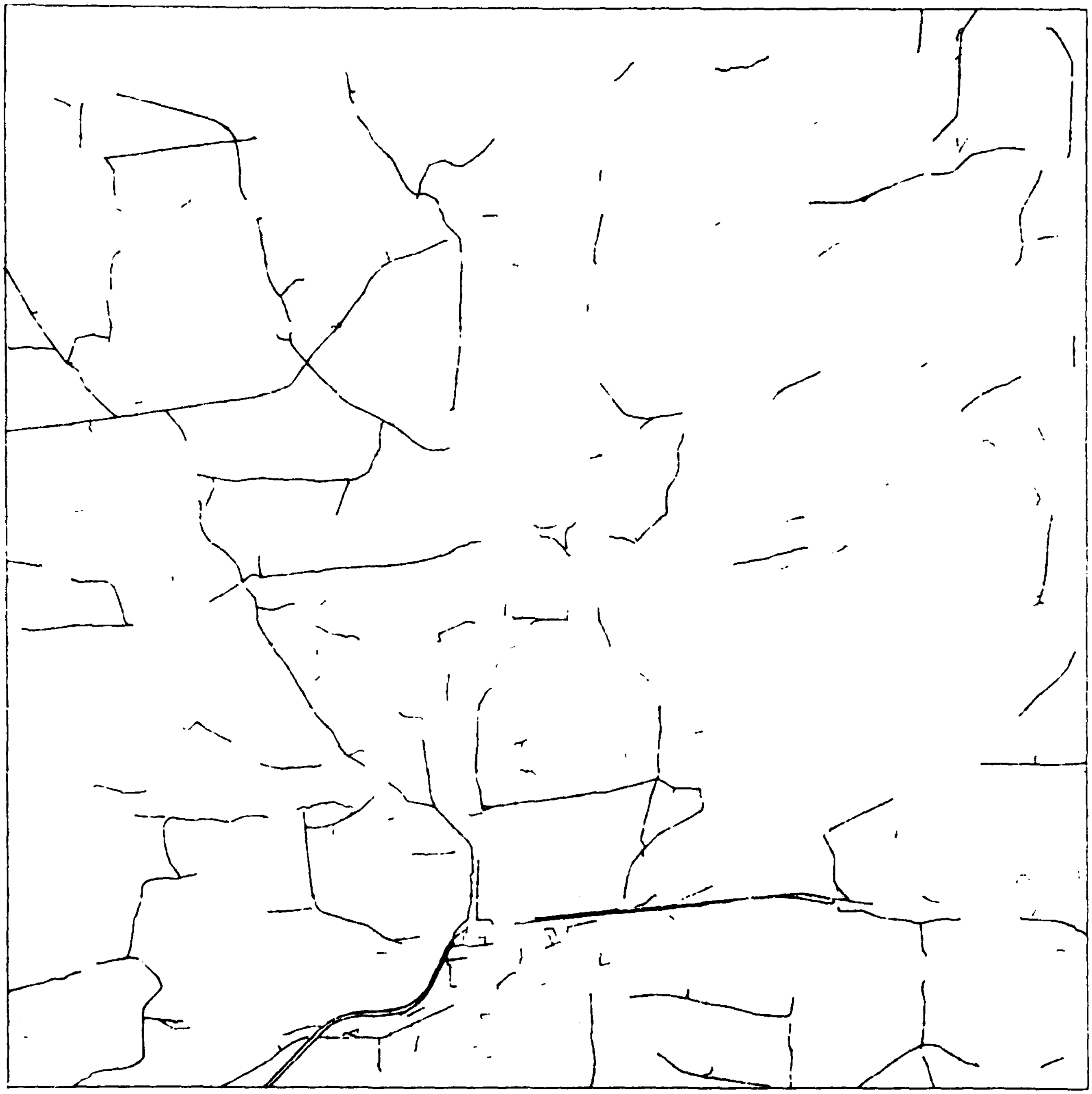


Fig. 11: Extraction results for a width tolerance of 2 to 5 pixels.

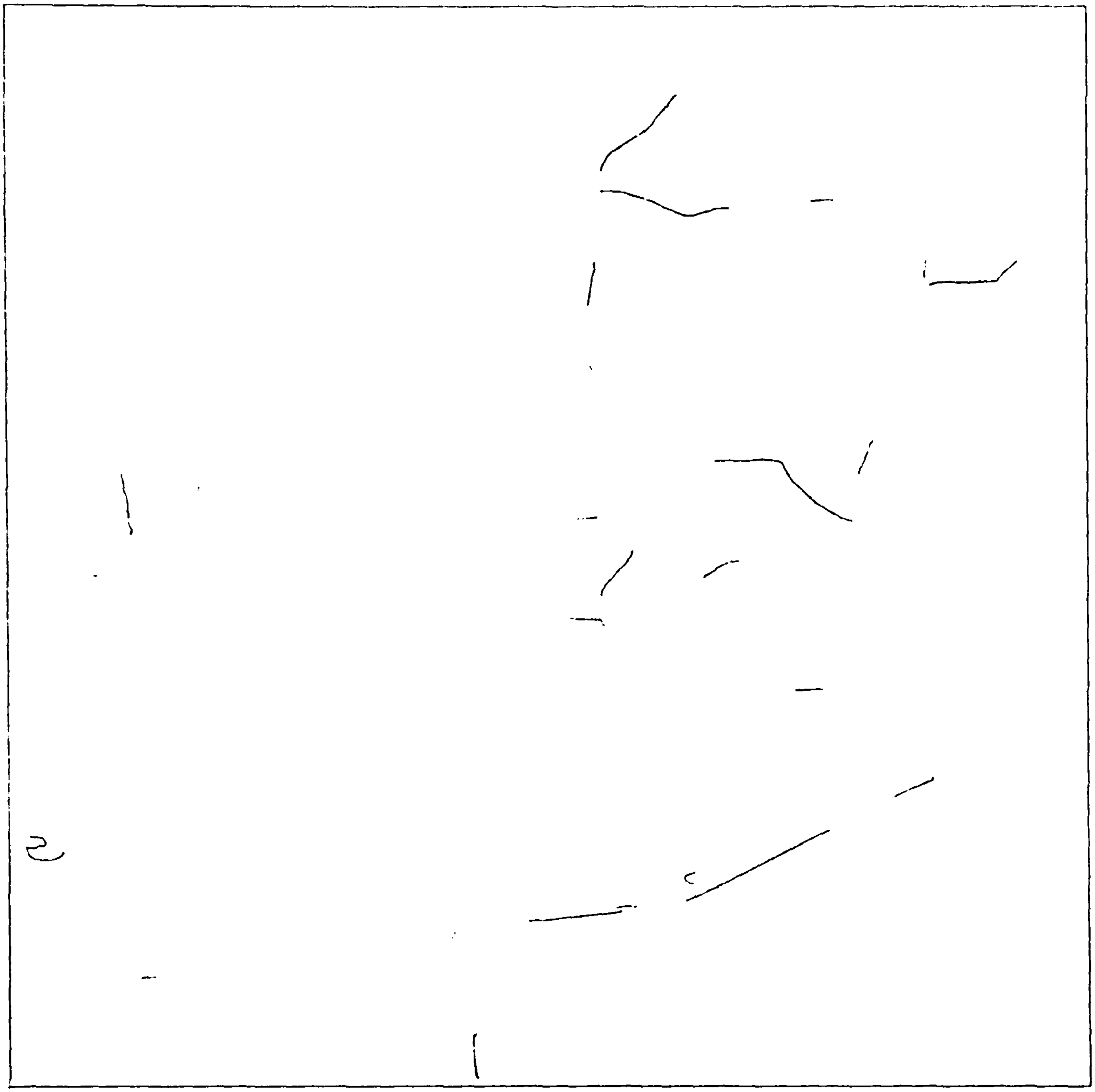


Fig. 12: Extraction results with a width tolerance of 4 to 7 pixels.

The next results shown in fig. 12, were produced by a run with an object width tolerance of 4 to 7 pixels. But this run was based on the results of the previous run (see fig. 11), so that we only extracted roads at locations, where the previous run had produced no result. We realized this proceeding by using the result matrix of each subimage (for details of the result format see /3/) to control the method for starting point recognition as well as the methods for object extraction. In contrast to this proceeding, the results presented in fig. 7, 8 and 9 had been produced completely independently, i.e. no result of one run had been used to control the process of the next run or to avoid certain areas, which had already been processed by the previous run.

If we do realize the control of the second run by the results of the previous run, as shown in fig. 11 and 12, we get only the complementary results with the benefit of a shorter computing time, which amounted to 2 : 54 hours for the complete mosaic of 289 subimages.

The superposition of the results of these two complementary runs is shown in fig. 13. This final result is comparable to the superposition of three runs (fig. 10) regarding the number of errors, the completeness, the amount of gaps and short object segments. A detailed analysis and assessment of the extraction results of some subimages will be presented in the following figures. As an overview, the respective subimages are indicated in fig. 14: subimages marked by % will be shown - together with the respective results - in a magnified representation; results of subimages marked by § will be explained on the basis of line printer representation. All magnified or detailed presentations show sections of fig. 10 (superposition of the results of the first three runs). Reference is also made to the total image (Fig. 6).

Fig. 13: Superposition of the last two complementary runs.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
52	53 %	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68
69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85
86 §	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102
103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119
120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136
137	138	139	140	141	142	143	144	145	146 %	147	148	149	150 %	151	152	153
154	155	156	157	158 %	159	160	161	162	163 %	164	165	166	167	168	169	170
171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187
188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204
205	206	207	208	209	210 % §	211	212	213	214	215 %	216	217	218	219	220	221
222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238
239	240	241	242	243 %	244	245	246	247	248	249	250	251	252	253	254	255
256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272
273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289

Fig. 14: Labeling of the subimages

Fig. 15 shows the situation of subimage No. 53. The extraction result is incomplete due to two gaps in the upper right part of the subimage, where the road obviously is hidden by trees. There is also a short incorrect segment of the result in the lower part of the subimage, where the road is not visible.

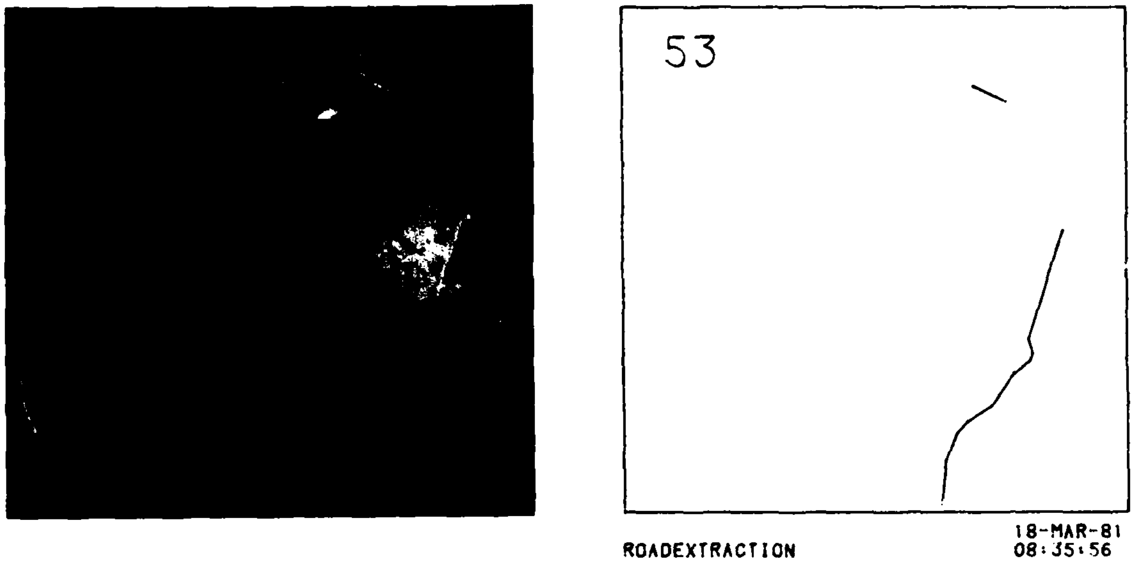


Fig. 15: Details of subimage No. 53.

Fig. 16 shows details of subimage No. 146. The gaps of the resulting road extraction are due to extremely low contrast between the object and the surrounding fields. The missing horizontal part at the upper end has been detected as a continuation from subimage No. 145 and is contained in the results of subimage No. 129 (refer to fig. 10).

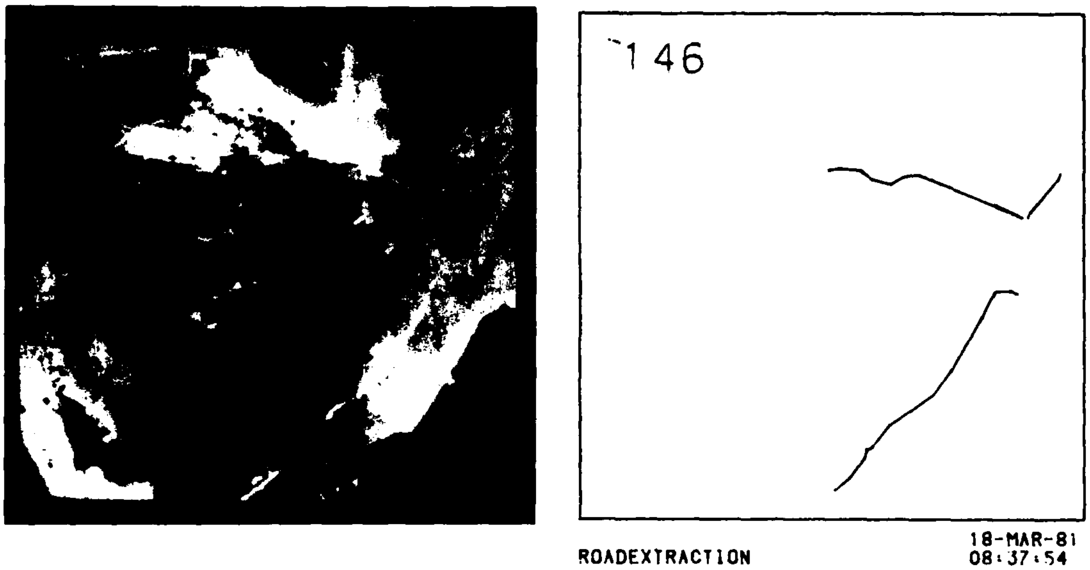


Fig. 16: Details of subimage No. 146.

Fig. 17 shows details of subimage No. 150. In the upper left part of the subimage, the road is not detectable due to very low contrast. In the lower left part of the subimage, the road is bordered by a strip of approx. equal width and brightness (probably strips of cut trees at the sides of the road) which alltogether constitute a line object much wider than a normal road. Thus this part of a road could not be detected even with object width tolerances up to 8 pixels.

Fig. 18 shows details of subimage No. 158. The continuation of the horizontal segment of the road in the middle of the subimage is invisible due to tree coverage. The vertical segment of the road in the right part of the subimage should have been extractable during the run with the bigger width tolerance, but no starting point seems to have been detected on that segment. This assessment leads to another suggestion for improvement of the overall performance: if roads of different width are to be

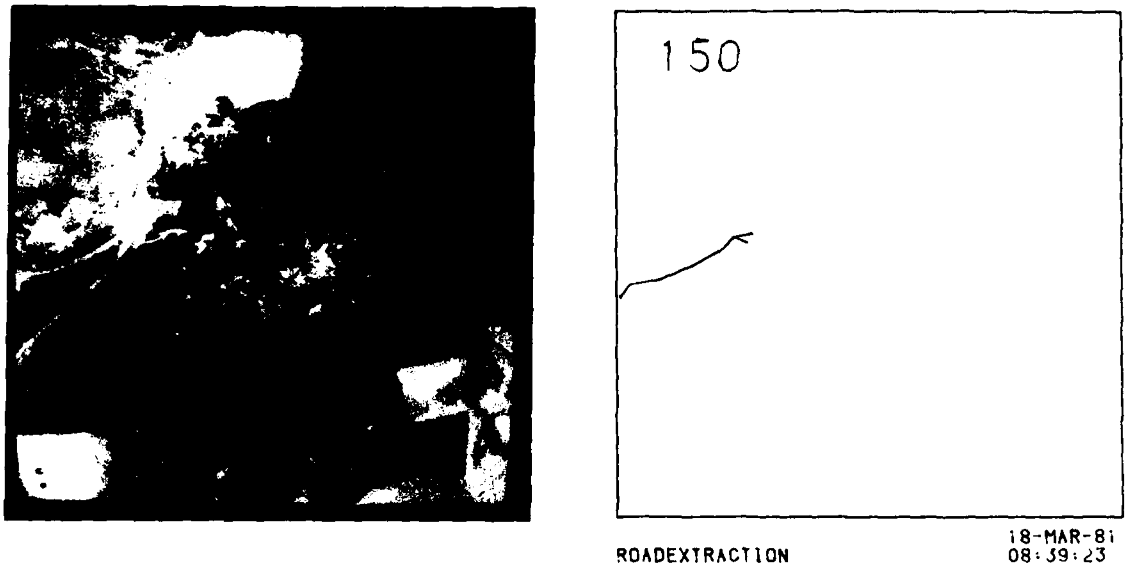


Fig. 17: Details of subimage No. 150.

extracted by a sequence of runs with different width tolerance values, don´t search for starting points during a successive run before the dead ends of the previous run have been used as starting points!

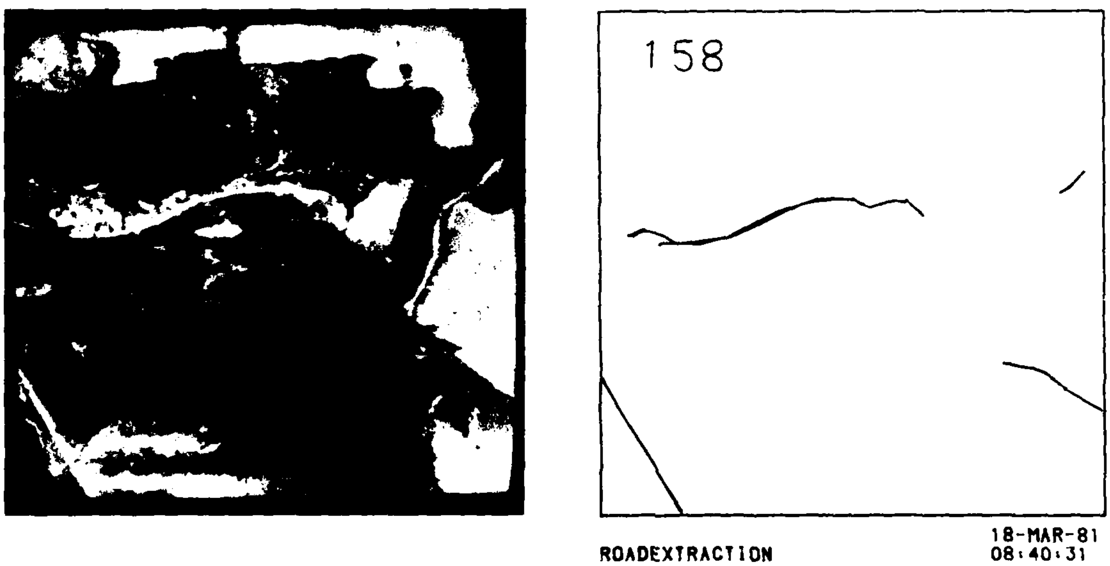


Fig. 18: Details of subimage No. 158.

Fig. 19 shows details of subimage No. 163. There is one gap in the vertical segment of the road, which is totally invisible and hence not extractable. The majority of the road network has been extracted correctly and completely.

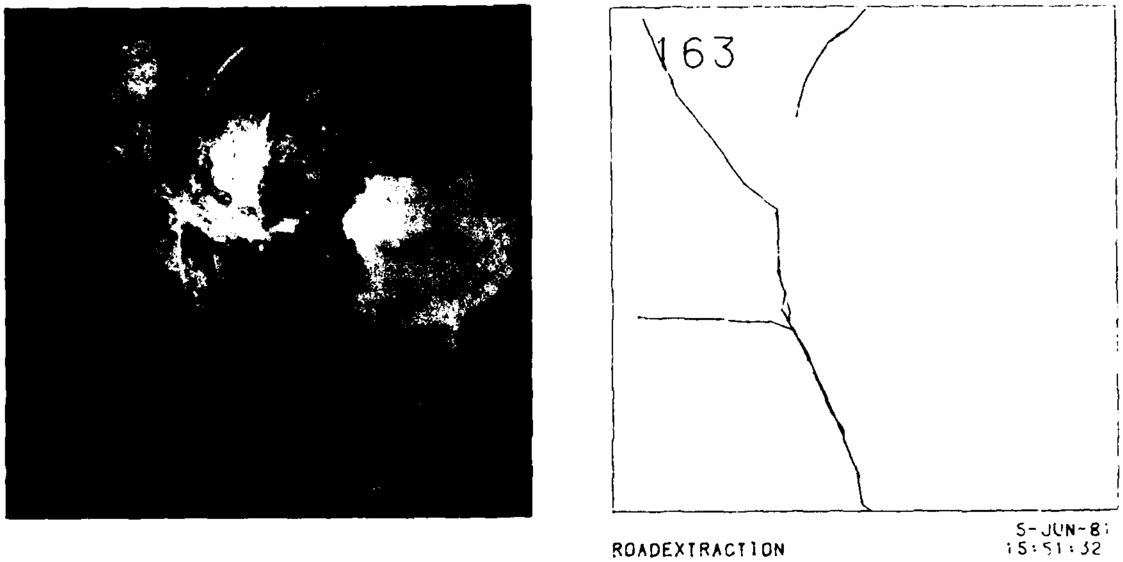


Fig. 19: Details of subimage No. 163.

Fig. 20 shows details of subimage No. 210. The gap in the centre of this subimage result is obviously due to presence of a farm yard which does not resemble to a road. The other missing parts of the roads in the upper right of the subimage could not be detected due to the intensive coverage by trees.

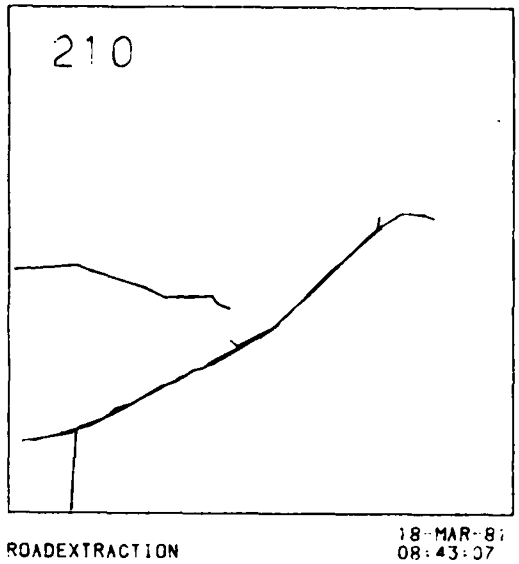


Fig. 20: Details of subimage No. 210.

We used this section of the aerial image in earlier tests and had success with the extraction of these parts of the roads (see fig. 37 to 50 in /1/). The success of those test results is due to the interactively chosen area of interest for the regional method, whereas the results of fig. 20 were produced automatically. This is another proof of the superior control of pattern recognition methods which can be executed by a human operator.

Fig. 21 shows details of subimage No. 215. There is only one vertical segment of the road missing in the upper right corner of the subimage which is due to the very low or even disappearing contrast with the fields. The majority of the road network has been detected completely and correctly.

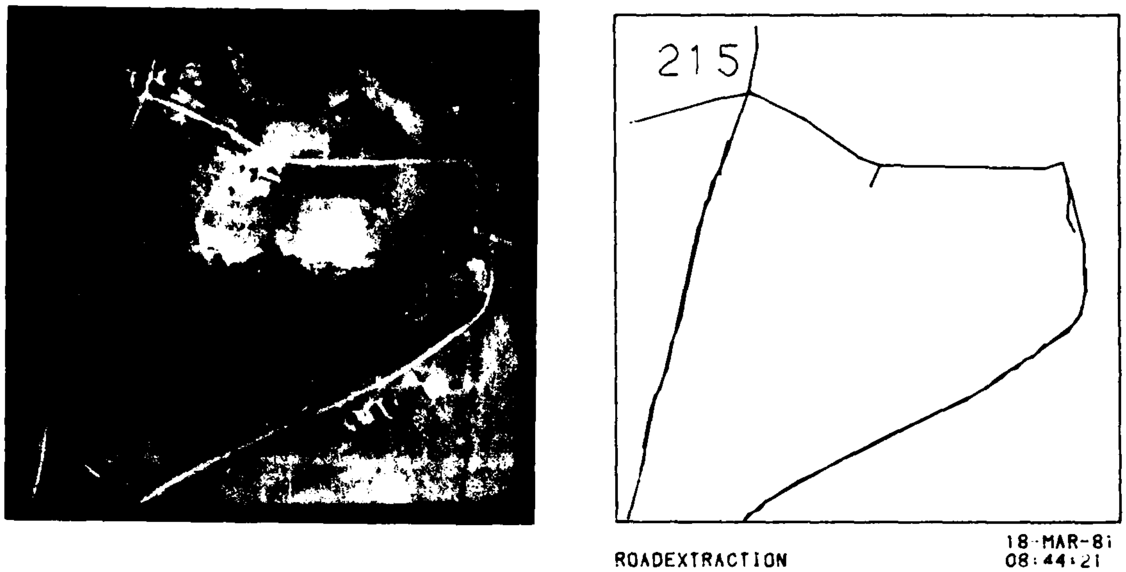


Fig. 21: Details of subimage No. 215.

Fig. 22 shows details of subimage No. 243. The only small gap, which could be filled by simple extrapolation, is obviously due to the farm yard which caused the extraction methods to stop.

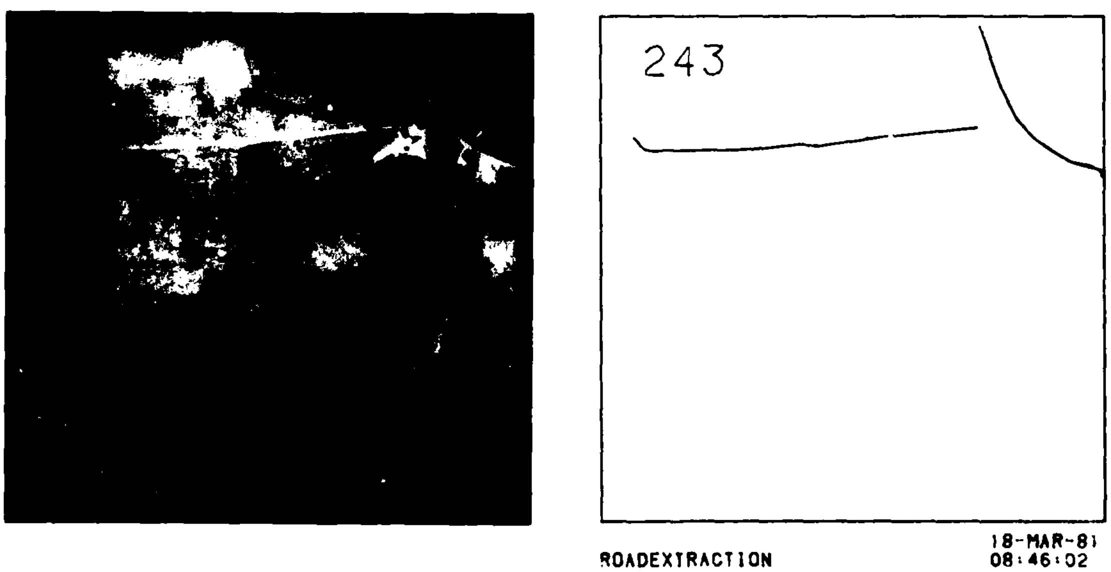


Fig. 22: Details of subimage No. 243.

Another product to assess the performance of the methods in detail can be presented by line printer outputs of the result matrix. Here we can see the number and location of starting points (marked by the character "S") and can assess the cooperation between both extraction methods, because the results produced by the local method are marked by the character "*", whereas the results produced by the regional method are marked by the character "o".

Fig. 23 shows a line printer output of the results of subimage No. 86. Only two starting points were used for the road extraction in this subimage and most of the results were produced by the local method due to the undistorted visibility.

Fig. 24 shows the line printer output of the results of subimage No. 210 (see also Fig. 20). It can be seen from this presentation that three starting points were used for the extraction of the two disconnected parts of the roads, that both methods had an equal share at the production of the results and that the local method decided to stop the extraction at the farm yard in the middle of this subimage.

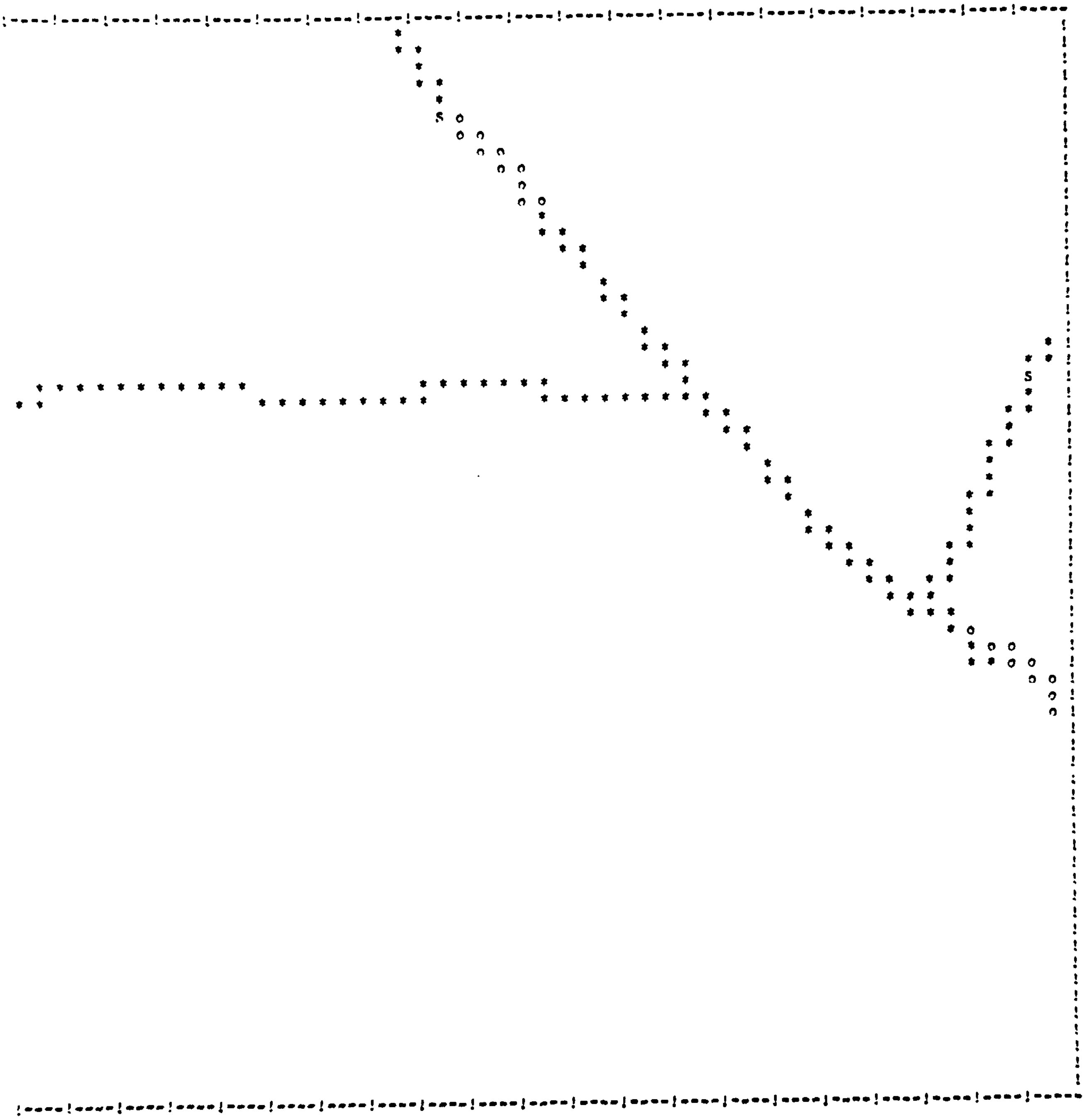


Fig. 23: Line printer output of the results of subimage No. 86.

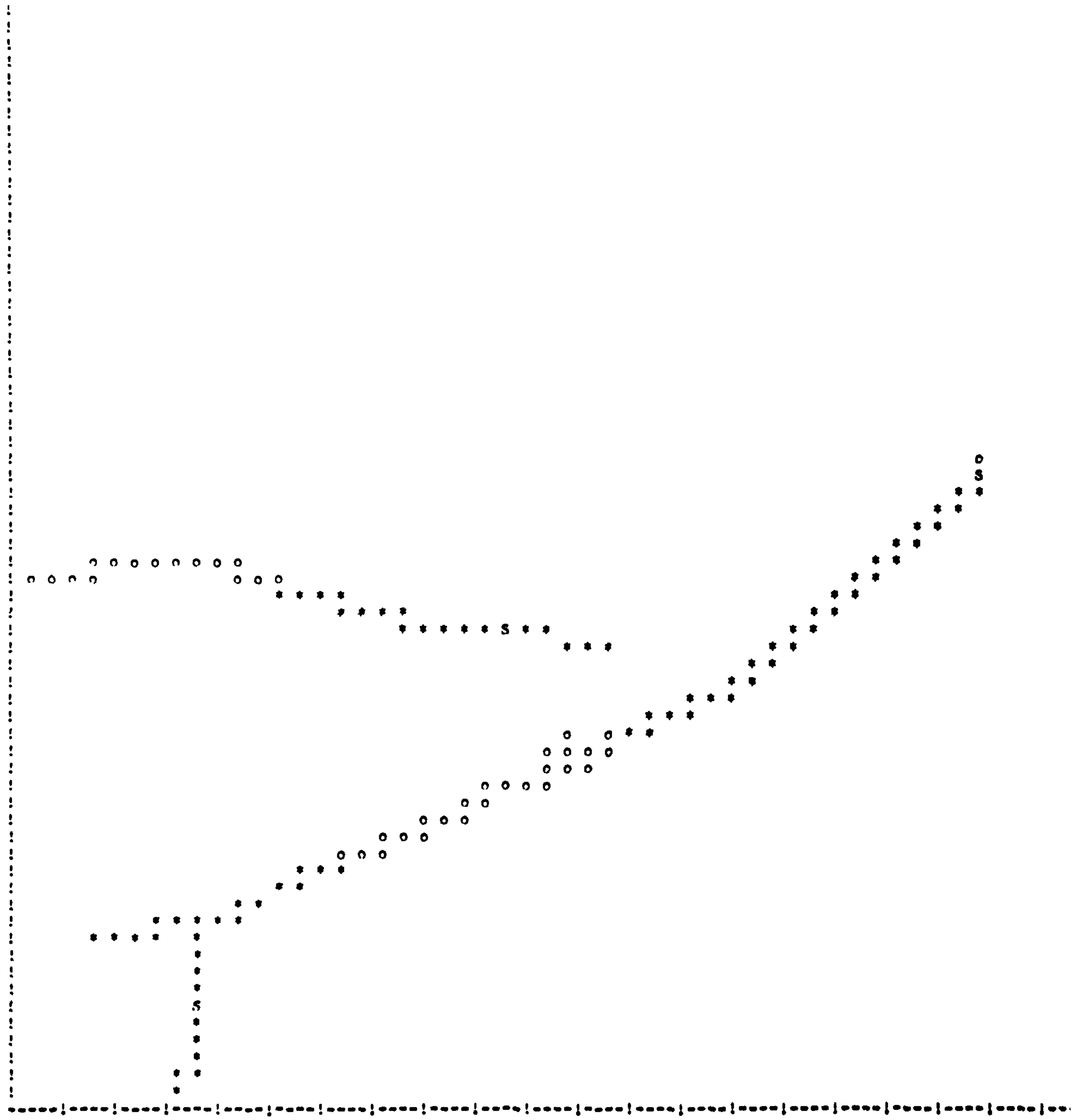


Fig. 24: Line printer output of the results of subimage No. 210.

5.2 <u>Results of the extraction of rivers from aerial photographs</u>

Only a few test images contained rivers. After some preliminary tests, a set of default values for the parameters could be derived with one exception: the width of rivers varies substantially and cannot be predetermined without knowledge about the scale of the image and the specific river to be extracted. Fig. 25 shows two test results of the method for the recognition of starting points on rivers. The short white strokes at the upper and lower edge of the image indicate the sample columns, which have been checked for starting points. For the first example, three starting points have been recognized, indicated by white strokes on the rivers; for the second example, which shows better contrasts and less variation of object properties, six starting points have been recognized, while only one would have been sufficient for the latter extraction process in both cases.

a) b)

<u>Fig. 25:</u> Two examples for the recognition of starting points of rivers.

The extraction of the river in fig. 25 a is shown in the following figure 26. The extraction result was produced by the cooperation

a) b) c)

Fig. 26: Extraction of the river shown in Fig. 25 a.

of the local and the regional method. Only the uppermost starting point has been necessary. The local method starts at that point to extract the river to the right until the edge of the image is reached and continues to the left of the starting point, until a distortion (see arrow in fig. 26 a) is reached. From this point the regional method pursues the extraction until a curve is reached (see arrow in Fig. 26 b). At that point the local method resumes the task until more distortions cause another call for the regional method which extracts the object down to the lower left corner of the image (see fig. 26 c).

5.3 Results of the extraction of highways from aerial photographs

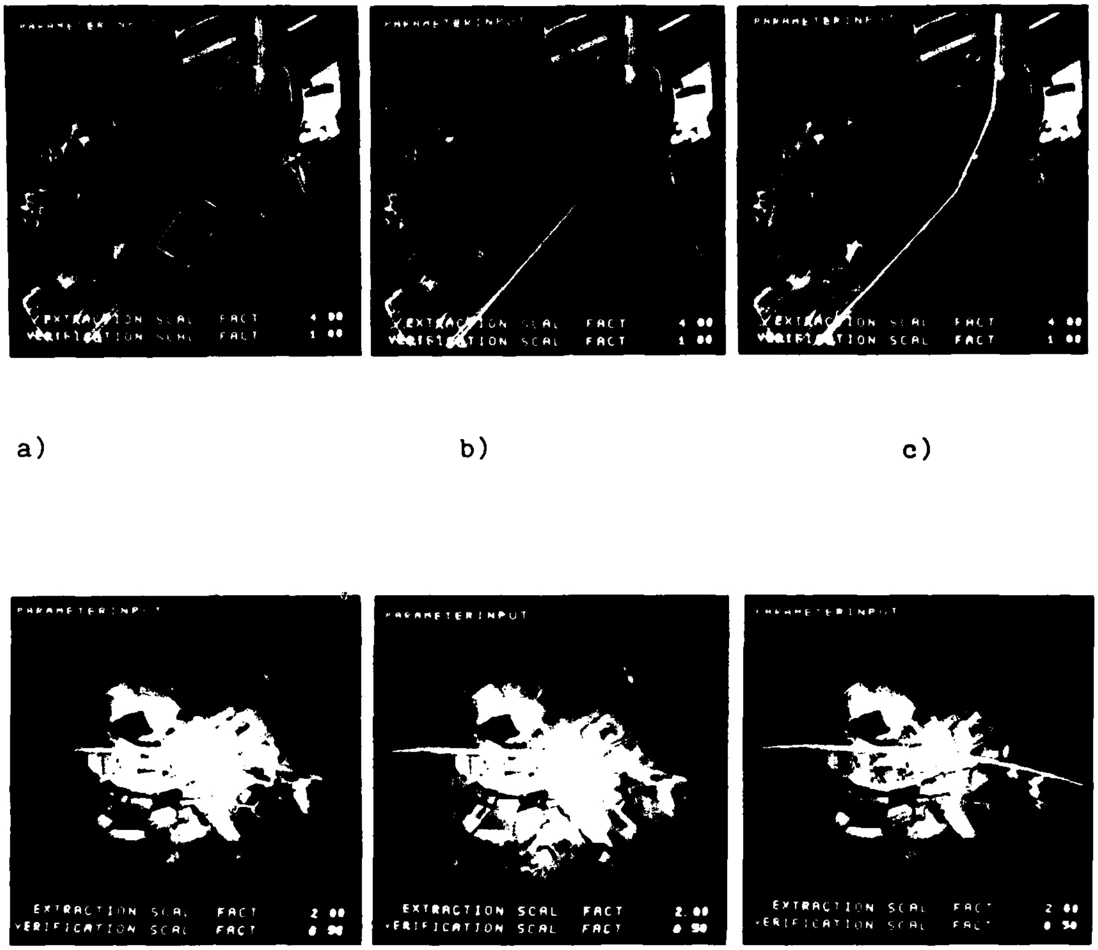
Two examples are presented to document the results of the extraction of highways. Fig. 27 shows the results of the recognition of starting points. Only very few sample lines respectively sample columns were analysed at a 1 : 4 reduced resolution of both images. Four preliminary starting points were detected in each image, two of which were accepted as true starting points by the verification algorithm, which processed the images at a resolution as shown in fig. 27. The respective locations are marked by white strokes superimposed to the image.

a)

b)

Fig. 27: Results of the recognition of starting points for highways.

Based on one starting point for each image, the extraction method produces the results shown in fig. 28. As the highways are mostly straight lined and contrast well with their surroundings, there are no major problems for the extraction. The highway exits in both examples were not detected, as the regional extraction method in its present implementation is not able to handle this task.



a) b) c)

d) e) f)

Fig. 28: Results of the extraction of highways.

6. Conclusions

It has been shown that the automatic extraction of a network of line objects from aerial images can be performed reliably and precisely. The success in generating correct extraction results is sometimes balanced by the incompleteness of the results, i.e. some parts of the objects which are occluded, distorted, or noisy, will remain undetected on the basis of these more or less local gray level analysis methods. To solve these problems automatically,

we need to develop methods of a higher degree of sophistication, which must be based on the evaluation of context of the near and far neighbourhood. Context, in this case, must be understood as preliminary results, object properties, possible or suspected object relations, implications of shadowing, etc.

Another problem, which remains unsolved as yet, is the extraction of line objects from densely populated areas, where a compound of regularly shaped, man made objects complicates the local gray level analysis to an extend, that the success of these methods is considerably lower than in rural areas. Again, to solve the extraction task in urban areas with a comparable success rate as shown above, we need methods with a higher degree of sophistication which must incorporate several operators, context evaluation, iterative improvement of preliminary results, knowledge based processing, etc.

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